TWO-DIMENSIONAL CHANNEL BONDING IN A HYBRID CDMA/FDMA FIXED WIRELESS ACCESS SYSTEM TO PROVIDE FINELY VARIABLE RATE CHANNELS

CLAIM OF PRIORITY FROM COPENDING PROVISIONAL PATENT APPLICATION:

This patent application claims priority from U.S. Provisional Patent Application No.: 60/243,972, filed on 10/27/2000, the disclosure of which is incorporated by reference herein in its entirety.

FIELD OF THE INVENTION:

This invention relates generally to wireless communications systems and methods, and relates in particular to hybrid Code Division Multiple Access (CDMA)/Frequency Division Multiple Access (FDMA) systems having a plurality of different possible data transmission rates.

BACKGROUND OF THE INVENTION:

Most cellular and fixed wireless access air-interfaces use either CDMA, FDMA or TDMA to provide logical channels to users.

Typically, CDMA and FDMA systems have one modulator and one demodulator in a subscriber unit, and a bank of modulators and demodulators in the base station. One link is typically established between each active subscriber unit and the base station. Thus, the modulators and demodulators typically communicate with each other using one pseudonoise (PN) code on one frequency at a time. In a CDMA application, it is possible that these channels may be variable rate data channels and use variable rate PN codes, such as those described in US Patent No.: 6,091,760, but these variable rate channels will typically be limited to power-of-two multiples of a basic rate. For example, if the basic rate channel were 32 kbps, then the possible rates achievable will be 64, 128, 256, 512, 1024, 2048 kbps, etc. Thus, if it is desirable to operate the link at 1050 kbps, then the next higher rate (2048 kbps) must be used, which is wasteful of system bandwidth.

Transmitting and receiving on multiple links in parallel to achieve additional rates is known in CDMA systems. For example, reference can be had to U.S. Patents 5,373,502, 5,442,625 and 5,166,951 in this regard.

SUMMARY OF THE INVENTION

A communications system employs the use of both CDMA and FDMA to provide a variable bandwidth waveform with multiple bonded transmitters and receivers that are agile in both frequency and PN code to permit a variable bandwidth and variable rate multiple access system.

In a first aspect the teachings provide the use of both CDMA and FDMA together to enable an improved concentration efficiency by making a larger pool of bandwidth available to each user. In a second aspect these teachings enable channel bonding across both code space and frequency space, thus making the system capable of operating within a variable (not necessarily contiguous) bandwidth and at a finely variable data rate.

A synchronous Code Division Multiple Access S-CDMA and Frequency Division Multiple Access FDMA communications system in accordance with these teachings includes a base site having a transmitter for transmitting a waveform, where the transmitter includes a plurality of frequency agile and PN code agile data modulators having an output coupled to a radio channel. The system further includes a subscriber unit having a receiver for receiving the transmitted waveform from the radio channel, where the receiver includes a plurality of frequency agile and PN code agile data demodulators.

There may be N modulators and N demodulators, each operable for communicating at data rates that are power of two multiples of a basic rate on a plurality of frequency subchannels within a channel. The N modulators and N demodulators operate with power of two multiples of the basic rate from a minimum rate to a maximum rate at a granularity that is an integer multiple of the basic rate.

Statistical concentration is achieved by providing the system with Y Mbps of aggregate capacity allocatable to X users simultaneously at rates of Y/X Mbps each, and by operating the N modulators and N demodulators to any one of Z frequency subchannels. In this case the useable bandwidth is Z times the Y Mbps bandwidth of any one channel, and Z*X users are supported simultaneously at rates of Y/X Mbps.

A bandwidth of any one subchannel is X MHz, and at least some of the plurality of modulators and demodulators are tuned to different ones of contiguous or non-contiguous X MHz sub-channels within a Y MHz channel, where Y> X. For example, X=3.5 and Y=14.

In the presently preferred, but not limiting embodiment the input data to the plurality of modulators is a punctured convolutional code, such as a rate ½, constraint length 7 code that is punctured to increase the rate of the code. The puncturing rate can be made adaptive to mitigate fading conditions. The output of the plurality of modulators can be coupled to the radio channel through an end-to-end raised-cosine Nyquist pulse shape filter.

BRIEF DESCRIPTION OF THE DRAWINGS

The above set forth and other features of the invention are made more apparent in the ensuing Detailed Description of the Invention when read in conjunction with the attached Drawings, wherein:

Fig. 1 is simplified block diagram of a wireless access reference model that pertains to the teachings of this invention;

Fig. 2 is block diagram of a physical (PHY) system reference model showing a major data flow path;

Fig. 3 shows an Error Control Coding (ECC) and scrambling technique for single CDMA channel;

Fig. 4 is a Table illustrating exemplary parameters for a 3.5MHz RF channelization;

Fig. 5 is a Table depicting an aggregate capacity and modulation factors versus modulation type and array size; and

Fig. 6 shows the use of multiple modulators and multiple demodulators in accordance with an aspect of these teachings.

DETAILED DESCRIPTION OF THE INVENTION

Disclosed herein is a PHY system intended for IEEE 802.16.3 and related standards, although those having skill in the art should realize that various aspects of these teachings have wider applicability.

The technique is based on a hybrid synchronous DS-CDMA (S-CDMA) and FDMA scheme using quadrature amplitude modulation (QAM) and trellis coding. For a

general background and benefits of S-CDMA with trellis-coded QAM one may refer to R. De Gaudenzi, C. Elia and R. Viola, "Bandlimited Quasi-Synchronous CDMA: A Novel Satellite Access Technique for Mobile and Personal Communication Systems," IEEE Journal on Selected Areas in Communications, Vol. 10, No. 2, February 1992, pp. 328-343, and to R. De Gaudenzi and F. Gianneti, "Analysis and Performance Evaluation of Synchronous Trellis-Coded CDMA for Satellite Applications," IEEE Transactions on Communications, Vol. 43, No. 2/3/4, February/March/April 1995, pp. 1400-1409.

The ensuing description focuses on a frequency division duplexing (FDD) mode. While a time division duplexing (TDD) mode is also within the scope of these teachings, the TDD mode is not discussed further.

What follows is an overview of the PHY teachings in accordance with this invention.

The system provides synchronous direct-sequence code division multiple access (DS-CDMA) for both upstream and downstream transmissions. The system further provides spread RF channel bandwidths from 1.75-7 MHz, depending on target frequency band, and a constant chip rate from 1-6 Mcps (Million chips per second)within each RF sub-channel with common I-Q spreading. The chip rate depends on channelization of interest (e.g. 3.5 MHz or 6 MHz). The system features orthogonal, variable-length spreading codes using Walsh-Hadamard designs with spread factors (SF) of 1, 2, 4, 8, 16, 32, 64 and 128 chips/symbol being supported, and also features unique spreading code sets for adjacent, same-frequency cells/sectors. Upstream and downstream power control and upstream link timing control are provided, as are single CDMA channel data rates from 32 kbps up to 16 Mbps depending on SF (spreading factor) and chip rate. In the preferred system S-CDMA channel aggregation is provided for the highest data rates.

Furthermore, in the presently preferred embodiment FDMA is employed for large bandwidth allocations with S-CDMA in each FDMA sub-channel, and S-CDMA/FDMA channel aggregation is used for the higher data rates. Code, frequency and/or time division multiplexing is employed for both upstream and downstream transmissions. Frequency division duplex (FDD) or time division duplex (TDD) can be employed, although as stated above the TDD mode of operation is not described further. The system features coherent QPSK and 16-QAM modulation with optional support for 64-QAM. End-to-end raised-cosine Nyquist pulse shape filtering is employed, as is adaptive coding, using high-rate punctured, convolutional coding (K=7) and/or Turbo coding (rates of 4/5, 5/6 and 7/8 are typical). Data

randomization using spreading code sequences is employed, as is linear equalization in the downstream with possible transmit pre-equalization for the upstream. Also featured is the use of space division multiple access (SDMA) using adaptive beam-forming antenna arrays (1 to 16 elements possible) at the base station.

Fig. 1 shows the wireless access reference model per the IEEE 802.16.3 FRD (see IEEE 802.16.3-00/02r4, "Functional Requirements for the 802.16.3 Interoperability Standard."). Within this model, the PHY technique in accordance with these teachings provides access between one or more subscriber stations (SS) 10 and base stations 11 to support the user equipment 12 and core network 14 interface requirements. An optional repeater 16 may be deployed.

In Fig. 2, the PHY reference model is shown. This reference model is useful in discussing the various aspects of the PHY technique. As is apparent, the SS 10 and BS transmission and reception equipment may be symmetrical. In a transmitter 20 of the BS 11 or the SS 10 there is an Error Control Coding (ECC) encoder 22 for incoming data, followed by a scrambling block 24, a modulation block 26 and a pulse shaping/pre-equalization block 28. In a receiver 30 of the BS 11 or the SS 10 there is a matched filter/equalization block 32, a demodulation block 34, a descrambling block 36 and an ECC decoder 38. These various components are discussed in further detail below.

The PHY interfaces with the Media Access Control (MAC) layer, carrying MAC packets and enabling MAC functions based on Quality of Service (QoS) requirements and Service Level Agreements (SLAs). As a S-CDMA system, the PHY interacts with the MAC for purposes of power and timing control. Both power and timing control originate from the BS 11, with feedback from the SS 10 needed for forward link power control. The PHY also interacts with the MAC for link adaptation (e.g. bandwidth allocation and SLAs), allowing adaptation of modulation formats, coding, data multiplexing, etc.

With regard to frequency bands and RF channel bandwidths, the primary frequency bands of interest for the PHY include the ETSI frequency bands from 1-3 GHz and 3-11 GHz as described in ETSI EN 301 055, Fixed Radio Systems; Point-to-multipoint equipment; Direct Sequence Code Division Multiple Access (DS-CDMA); Point-to-point digital radio in frequency bands in the range 1 GHz to 3 GHz, and in ETSI EN 301 124, Transmission and Multiplexing (TM); Digital Radio Relay Systems (DRRS); Direct Sequence Code Division Multiple Access (DS-CDMA) point-to-multipoint DRRS in frequency bands in the range 3 GHz to 11 GHz, as well

as with the MMDS/MDS (digital TV) frequency bands. In ETSI EN 301 124, the radio specifications for DS-CDMA systems in the fixed frequency bands around 1.5, 2.2, 2.4 and 2.6 GHz are given, allowing channelizations of 3.5, 7, 10.5 and 14 MHz. Here, the Frequency Division Duplex (FDD) separation is specific to the center frequency and ranges from 54 to 175 MHz. In ETSI EN 301 124, Transmission and Multiplexing (TM); Digital Radio Relay Systems (DRRS); Direct Sequence Code Division Multiple Access (DS-CDMA) point-to-multipoint DRRS in frequency bands in the range 3 GHz to 11 GHz., the radio characteristics of DS-CDMA systems with fixed frequency bands centered around 3.5, 3.7 and 10.2 GHz are specified, allowing channelizations of 3.5, 7, 14, 5, 10 and 15 MHz. Here, FDD separation is frequency band dependant and ranges from 50 to 200 MHz. Also of interest to these teachings are the MMDS/ITSF frequency bands between 2.5 and 2.7 GHz with 6 MHz channelizations.

With regard to multiple access, duplexing and multiplexing, the teachings herein provide a frequency division duplex (FDD) PHY using a hybrid S-CDMA/FDMA multiple access scheme with SDMA for increased spectral efficiency. In this approach, a FDMA sub-channel has an RF channel bandwidth from 1.75 to 7 MHz. The choice of FDMA sub-channel RF channel bandwidth is dependent on the frequency band of interest, with 3.5 MHz and 6 MHz being typical per the IEEE 802.16.3 FRD. Within each FDMA sub-channel, S-CDMA is used with those users transmitting in the upstream and downstream using a constant chipping rate from 1 to 6 Mchips/second. While TDD could be used in a single RF sub-channel, this discussion is focused on the FDD mode of operation. Here, FDMA sub-channel(s) are used in the downstream while at least one FDMA sub-channel is required for the upstream. The approach is flexible to asymmetric data traffic, allowing more downstream FDMA sub-channels than upstream FDMA sub-channels when traffic patterns and frequency allocation warrant. Based on existing frequency bands, typical upstream/downstream FDMA channel separation range from 50 to 200 MHz.

Turning now to the Synchronous DS-CDMA (S-CDMA) aspects of these teachings, within each FDMA sub-channel, S-CDMA is used in both the upstream and the downstream directions. The chipping rate is constant for all SS with rates ranging from 1 to 6 Mchips/second depending on the FDMA RF channel bandwidth. Common I-Q spreading is performed using orthogonal, variable-length spreading codes based on Walsh-Hadamard designs with spread factors ranging from 1 up to 128 chips per symbol (see, for example, E. Dinan and G. Jabbari, "Spreading Codes for Direct Sequence CDMA and Wideband CDMA Cellular Networks," IEEE Communications Magazine, September 1998, pp. 48-54. For multi-cell deployments

with low frequency reuse, unique spreading code sets are used in adjacent cells to minimize interference.

It should be noted that an aspect of these teachings is a symmetric waveform within each FDMA sub-channel, where both the upstream and downstream utilize the same chipping rate (and RF channel bandwidth), spreading code sets, modulation, channel coding, pulse shape filtering, etc.

Referring now to Code and Time Division Multiplexing and channel aggregation, with a hybrid S-CDMA/FDMA system it is possible to multiplex data over codes and frequency sub-channels. Furthermore, for a given code or frequency channel, time division multiplexing could also be employed. In the preferred approach, the following multiplexing scheme is employed.

For the downstream transmission with a single FDMA sub-channel, the channel bandwidth (i.e. capacity measured in bits/second) is partitioned into a single TDM pipe and multiple CDM pipes. The TDM pipe may be created via the aggregation of multiple S-CDMA channels. The purpose of this partition is based on the desire to provide Quality of Service (QoS). Within the bandwidth partition, the TDM pipe would be used for best effort service (BES) and for some assured forwarding (AF) traffic. The CDM channels would be used for expedited forwarding (EF) services, such as VoIP connections or other stream applications, where the data rate of the CDM channel is matched to the bandwidth requirement of the service.

The downlink could be configured as a single TDM pipe. In this case a time slot assignment may be employed for bandwidth reservation, with typical slot sizes ranging from 4–16 ms in length. While a pure TDM downlink is possible in this approach, it is preferred instead to employ a mixed TDM/CDM approach. This is so because long packets can induce jitter into EF services in a pure TDM link. Having CDMA channels (single or aggregated) dedicated to a single EF service (or user) reduces jitter without the need for packet fragmentation and reassembly. Furthermore, these essentially "circuit-switched" CDM channels would enable better support of legacy circuit-switched voice communications equipment and public switched telephone networks.

For the upstream, the preferred embodiment employs a similar partition of TDM/CMD channels. The TDM channel(s) would be used for random access, using a slotted-Aloha protocol. In keeping with a symmetric waveform, recommended burst lengths are on the order of the slot times for the downlink, ranging from 4-16

ms. Multi-slot bursts are possible. The BS 11 monitors bursts from the SS 10 and allocates CDMA channels to SSs upon recognition of impending bandwidth requirements or based on service level agreements (SLAs). As an example, a BS 11 recognizing the initiation of a VoIP connection could move the transmission to a dedicated CDMA channel with a channel bandwidth of 32 kbps.

When multiple FDMA sub-channels are present in the upstream or downstream directions, similar partitioning could be used. Here, additional bandwidth exists which implies that more channel aggregation is possible. With a single TDM channel, data may be multiplexed across CDMA codes and across frequency sub-channels.

With regard now to Space Division Multiple Access (SDMA) extensions, a further aspect of this multiple access scheme involves the use of SDMA using adaptive beamforming antennas. Reference can be made to J. Liberti and T. Rappaport, Smart Antennas for Wireless CDMA, Prentice-Hall PTR, Upper Saddle River, NJ, 1997, for details of beamforming with CDMA systems.

In accordance with the teachings herein there is provided an adaptive antenna array at the BS 11, with fixed beam SS antennas. In this approach, S-CDMA/FDMA channels can be directed at individual SSs. The isolation provided by the beamforming allows the CDMA spreading codes to be reused within the same cell, greatly increasing spectral efficiency. Beamforming is best suited to CDM rather than TDM channels. In the downstream, TDM would employ beamforming on a per slot or burst basis, increasing complexity. In the upstream, beamforming would be difficult since the BS 11 would need to anticipate transmission from the SS in order to form the beams appropriately. In either case, reuse of CDMA spreading codes in a TDM-only environment would be difficult. With CDM, however, the BS 11 may allocate bandwidth (i.e. CDMA channels) to SS 10 based on need, or on SLAs. Once allocated, the BS 11 forms a beam to the SS 10 to maximize signal-to-interference ratios. Once the beam is formed, the BS 11 may allocate the same CDMA channel to one or more other SSs in the cell. It is theoretically possible for the spectral efficiency of the cell to scale linearly with the number of antennas in the BS array.

SDMA greatly favors the approach of "fast circuit-switching" over pure, TDM packet-switching in a CDMA environment. By "fast circuit-switching", what is implied is that packet data services are handled using dedicated connections, which are allocated and terminated based on bandwidth requirements and/or SLAs. An important consideration when providing effective packet-services using this approach

lies in the ability of the BS 11 to rapidly determine bandwidth needs, and to both allocate and terminate connections rapidly. With fast channel allocation and termination, SDMA combined with the low frequency reuse offered by S-CDMA is a preferred option, in terms of spectral efficiency, for FWA applications.

A discussion is now made of waveform specifications. The waveform includes the channel coding 22, scrambling 24, modulation 26 and pulse shaping and equalization functions 28 of the air interface, as depicted in Fig. 2. Also included are waveform control functions, including power and timing control. In the presently preferred PHY, each CDMA channel (i.e. spreading code) uses a common waveform, with the spreading factor dictating the data rate of the channel.

With regard to the Error Control Coding (ECC) function 22 of Fig. 2, the ECC is preferably high-rate and adaptive. High rate codes are used to maximize the spectral efficiency of BWA systems using S-CDMA systems that are code-limited. In code-limited systems, the capacity is limited by the code set cardinality rather than the level of the multi-user interference. Adaptive coding is preferred in order to improve performance in multipath fading environments. For the coding options, and referring as well to Fig. 3, the baseline code is preferably a punctured convolutional code (CC). The constituent code may be the industry standard, rate ½, constraint length 7 code with generator $(133/171)_8$. Puncturing is used to increase the rate of the code, with rates of 3/4, 4/5, 5/6 or 7/8 supported using optimum free distance puncturing patterns. The puncturing rate of the code may be adaptive to mitigate fading conditions. For decoding (block 38 of Fig. 2), a Viterbi decoder is preferred. Reference in this regard can be made again to the above-noted publication R. De Gaudenzi and F. Gianneti, "Analysis and Performance Evaluation of Synchronous Trellis-Coded CDMA for Satellite Applications," IEEE Transactions on Communications, Vol. 43, No. 2/3/4, February/March/April 1995, pp. 1400-1409, for an analysis of trellis-coded S-CDMA.

Turbo coding, including block turbo codes and traditional parallel and serial concatenated convolutional codes, are preferably supported as an option at the rates suggested above. In Fig. 3, the CC/Turbo coding is performed in block 22A, the puncturing in block 22B, and the scrambling can be performed using an XOR 24A that receives a randomizing code.

Each CDMA channel is preferably coded independently. Independent coding of CDMA channels furthers the symmetry of the upstream and downstream waveform and enables a similar time-slot structure on each CDMA channel. The upstream and

downstream waveform symmetry aids in cost reduction, as the SS 10 and BS 11 baseband hardware can be identical. The independent coding of each S-CDMA/FDMA channel is an important distinction between this approach and other multi-carrier CDMA schemes.

Randomization is preferably implemented on the coded bit stream. Rather than using a traditional randomizing circuit, it is preferred, as shown in Fig. 3, to use randomizing codes derived from the spreading sequences used by the transmitting station. Using the spreading codes allows different randomizing sequences to be used by different users, providing more robust randomization and eliminating problems with inter-user correlated data due to periodic sequences transmitted (e.g. preambles). Since the receiving station has knowledge of the spreading codes, de-randomization is trivial. Randomization may be disabled on a per channel or per symbol basis. Fig. 3 thus depicts the preferred channel coding and scrambling method for a single CDMA channel.

With regard to the modulation block 26, both coherent QPSK and square 16-QAM modulation formats are preferably supported, with optional support for square 64-QAM. Using a binary channel coding technique, Gray-mapping is used for constellation bit-labeling to achieve optimum decoded performance. This combined coding and modulation scheme allows simple Viterbi decoding hardware designed for binary codes to be used. Differential detection for all modulation formats may be supported as an option. Depending on the channel coding, waveform spectral efficiencies from 1 to 6 information bits/symbol are realized.

The modulation format utilized is preferably adaptive based on the channel conditions and bandwidth requirements. Both upstream and downstream links are achievable using QPSK waveform provided adequate SNR. In environments with higher SNR, up and downstream links may utilize 16-QAM and /or 64-QAM modulation formats for increased capacity and spectral efficiency. The allowable modulation format depends on the channel conditions and the channel coding being employed on the link.

In the preferred embodiment end-to-end raised-cosine Nyquist pulse shaping is applied by block 28 of Fig. 2, using a minimum roll-off factor of 0.25. Pulse shape filtering is designed to meet relevant spectral masks, mitigate inter-symbol interference (ISI) and adjacent FDMA channel interference.

To mitigate multipath fading, a linear equalizer 32 is preferred for the downstream.

Equalizer training may be accomplished using a preamble, with decision-direction used following initial training. With S-CDMA, equalizing the aggregate signal in the downlink effectively equalizes all CDMA channels. Multipath delay spread of less than 3 μs is expected for Non-Line Of Sight (NLOS) deployments using narrow-beam (10-20°) subscriber station 10 antennas (see, for example, J. Porter and J. Thweat, "Microwave Propagation Characteristics in the MMDS Frequency Band," Proceedings of IEEE International Conf. On Communications (ICC) 2000, New Orleans, LA, USA, June 2000, and V. Erceg, et al, "A Model for the Multipath Delay Profile of Fixed Wireless Channels," IEEE Journal on Selected Areas in Communications (JSAC), Vol. 17, No. 3, March 1999, pp. 399-410.

The low delay spread allows simple, linear equalizers with 8-16 taps that effectively equalize most channels. For the upstream, pre-equalization may be used as an option, but requires feedback from the subscriber station 10 due to frequency division duplexing.

Timing control is required for S-CDMA. In the downstream, timing control is trivial. However, in the upstream timing control is under the direction of the BS 11. Timing control results in reduced in-cell interference levels. While infinite in-cell signal to interference ratios are theoretically possible, timing errors and reduction in code-orthogonality from pulse shape filtering allows realistic signal to in-cell interference ratios from 30-40 dB. In asynchronous DS-CDMA (A-CDMA) systems, higher in-cell interference levels exist, less out-of-cell interference can be tolerated and higher frequency reuse is needed to mitigate out-of-cell interference(see, for example, T. Rappaport, Wireless Communications: Principles and Practice, Prentice-Hall PTR, Upper Saddle River, NJ, 1996, pp. 425-431. The ability of timing-control to limit in-cell interference is an important aspect of achieving a frequency reuse of one in a S-CDMA system.

Power control is also required for S-CDMA systems. Power control acts to mitigate in-cell and out-of-cell interference while also ensuring appropriate signal levels at the SS 10 or the BS 11 to meet bit error rate (BER) requirements. For a SS 10 close to the BS 11, less transmitted power is required, while for a distant SS 10, more transmit power is required in both the up and downstream. As with timing control, power control is an important aspect of achieving a frequency reuse of one.

Turning now to a discussion of capacity, spectral efficiency and data rates, for a single, spread FDMA channel, the presently preferred S-CDMA waveform is capable of providing channel bandwidths from 1 to 16 Mbps. Using variable-length spreading

codes, each CDMA channel can be configured to operate from 32 kbps (SF=128) to 16 Mbps (SF=1), with rates depending on the modulation, coding and RF channel bandwidths. With S-CDMA channel aggregation, high data rates are possible without requiring a SF of one. In general, the use of S-CDMA along with the presently preferred interference mitigation techniques enable the system to be code-limited. Note, mobile cellular A-CDMA systems are always interference-limited, resulting in lower spectral efficiency. Recall also that in code-limited systems, the capacity is limited by the code set cardinality rather than the level of the multi-user interference. In a code-limited environment, the communications channel bandwidth of the system is equal to the communications channel bandwidth of the waveform, assuming a SF of one. In the Table shown in Fig. 4 sample parameters are shown for a hypothetical system using different coded modulation schemes and assuming a code-limited DS-CDMA environment. The Table of Fig. 4 illustrates potential performance assuming a single 3.5 MHz channel in both the upstream and downstream. The numbers reported apply to both the upstream and downstream directions, meaning that upwards of 24 Mbps full duplex is possible (12 Mbps upstream and 12 Mbps downstream). With additional FDMA RF channels or large RF channels (e.g. 6 MHz), additional communication bandwidth is possible with the same modulation factors from the Table. As an example, allocation of 14 MHz could be serviced using 4 FDMA RF channels with the parameters described in the Table of Fig. 4. At 14 MHz, peak data rates to a given SS 10 of up to 48 Mbps are achievable, with per-CDMA channel data rates scaling up from 32 kbps. The channel aggregation method in accordance with these teachings is very flexible in servicing symmetric versus asymmetric traffic, as well as for providing reserved bandwidth for QoS and SLA support.

With regard to multi-cell performance, to this point both the capacity and spectral efficiency have been discussed in the context of a single, isolated cell. In a multi-cell deployment, S-CDMA enables a true frequency reuse of one. With S-CDMA, there is no need for frequency planning, and spectral efficiency is maximized. With a frequency reuse of one, the total system spectral efficiency is equal to the modulation factor of a given cell. Comparing S-CDMA to a single carrier TDMA approach, with a typical frequency reuse of 4, TDMA systems must achieve much higher modulation factors in order to compete in terms of overall system spectral efficiency. Assuming no sectorization and a frequency reuse of one, S-CDMA systems can achieve system spectral efficiencies from 1 to 6 bps/Hz, with improvements being possible with SDMA.

While frequency reuse of one is theoretically possible for DS-CDMA, the true

allowable reuse of a specific deployment is dependent on the propagation environment (path loss) and user distribution. For mobile cellular systems, it has been shown that realistic reuse factors range from 0.3 up to 0.7 for A-CDMA: factors that are still much higher than for TDMA systems. In a S-CDMA system, in-cell interference is mitigated by the orthogonal nature of the S-CDMA, implying that the dominant interference results from adjacent cells. For the fixed environments using S-CDMA, true frequency reuse of one can be achieved for most deployments using directional SS antennas and up and downstream power control to mitigate levels of adjacent cell interference. In a S-CDMA environment, true frequency reuse of one implies that a cell is code-limited, even in the presence of adjacent cell interference.

For sectorized deployments with S-CDMA, a frequency reuse of two is required to mitigate the interference contributed by users on sector boundaries. In light of this reuse issue, it is preferred to use SDMA with adaptive beamforming rather than sectorization to improve cell capacity.

Since spectral efficiency translates directly into cost, the possibility of a frequency reuse of one is an important consideration.

The use of SDMA in conjunction with S-CDMA offers the ability to dramatically increase system capacity and spectral efficiency. SDMA uses an antenna array at the BS 11 to spatially isolate same code SSs 10 in the cell. The number of times that a code may be reused within the same cell is dependent upon the number of antenna elements in the array, the array geometry, the distribution of users in the cell, the stability of the channel, and the available processing power. Theoretically, in the absence of noise, with an M element antenna array it is possible to reuse each code sequence M times, thereby increasing system capacity by a factor of M. In practice, the code reuse is slightly less than M due to implementation loss, frequency selective multipath fading, and receiver noise. Regardless, significant capacity gains are achievable with SDMA. With appropriate array geometry and careful grouping of users sharing CDMA codes, it is possible to achieve a code reuse of $0.9M$ or better.

In an actual deployment the number of antenna elements is limited by the available processing power, the physical tower constraints, and system cost (e.g. the number of additional RF front ends (RFFEs)). Selected array sizes vary depending upon the required capacity of the given cell on a cell-by-cell basis. The Table shown in Fig. 5 illustrates the achievable aggregate capacity and modulation factor with typical array sizes, assuming a code reuse equal to the number of antenna elements. The aggregate capacity is defined as the total data rate of the BS 11. Modulation factors exceeding

56 bps/Hz are achievable with 64 QAM and a sixteen-element antenna array. It should be noted that while SDMA increases the capacity of cell, it does not increase the peak data rate to a given SS 10.

The PHY system disclosed herein is very flexible. Using narrowband S-CDMA channels, the PHY system can adapt to frequency allocation, easily handling non-contiguous frequency allocations. The data multiplexing scheme allows great flexibility in servicing traffic asymmetry and support of traffic patterns created by higher-layer protocols such as TCP.

Deployments using the disclosed PHY are also very scalable. When traffic demands increase, new frequency allocation can be used. This involves adding additional FDMA channels, which may or may not be contiguous with the original allocation. Without additional frequency allocation, cell capacity can be increased using an adaptive antenna array and SDMA.

The high spectral efficiency of the disclosed waveform leads to cost benefits. High spectral efficiency implies less frequency bandwidth is required to provide a certain amount of capacity.

Using a symmetric waveform (i.e., a waveform that is the same in the upstream and downstream directions) is a cost saving feature, allowing the use of common baseband hardware in the SS 10 and the BS 11. The use of CDMA technology also aids in cost reduction, as some CDMA technology developed for mobile cellular applications may be applicable to gain economies of scale.

As a spread spectrum signal, the preferred waveform offers inherent robustness to interference sources. Interference sources are reduced by the spreading factor, which ranges from 1 to 128 (interference suppression of 0 to 21 dB.) At the SS 10, equalization further suppresses narrowband jammers by adaptively placing spectral nulls at the jammer frequency. Additional robustness to interference is achieved by the directionality of the SS antennas, since off-boresight interference sources are attenuated by the antenna pattern in the corresponding direction. At the BS 11, the antenna array used to implement SDMA offers the additional benefit of adaptively steering nulls towards unwanted interference sources.

The presently preferred waveform exhibits several properties that make it robust to channel impairments. The use of spread spectrum makes the waveform robust to frequency selective fading channels through the inherent suppression of inter-chip

interference. Further suppression of inter-chip interference is provided by equalization at the SS 10. The waveform is also robust to flat fading channel impairments. The adaptive channel coding provides several dB of coding gain. The antenna array used to implement SDMA also functions as a diversity combiner. Assuming independent fading on each antenna element, diversity gains of M are achieved, where M is equal to the number of antenna elements in the array. Finally, since the S-CDMA system is code-limited rather than interference limited the system may run with a large amount of fade margin. Even without equalization or diversity, fade margins on the order of 10 dB are possible. Therefore, multipath fades of 10 dB or less do not increase the BER beyond the required level.

The adaptive modulation also provides some robustness to radio impairments. For receivers with larger phase noise, the QPSK modulation offers more tolerance to receiver phase noise and filter group delay. The adaptive equalizer at the SS 10 reduces the impact of linear radio impairments. Finally, the use of clipping to reduce the peak-to-average power ratio of the transmitter signal helps to avoid amplifier saturation, for a given average power output.

An important distinction between the presently preferred embodiment and a number of other CDMA approaches is the use of a synchronous upstream, which allows the frequency reuse of one. Due to some similarity with mobile cellular standards, cost savings are possible using existing, low-cost CDMA components and test equipment.

The presently preferred PHY is quite different from cable modem and xDSL industry standards, as well as existing IEEE 802.11 standards. However, with a spreading factor of one chip/symbol, the PHY supports a single-carrier QAM waveform similar to DOCSIS 1.1 and IEEE 802.16.1 draft PHY (see "Data-Over-Cable Service Interface Specifications: Radio Frequency Interface Specification", SP-RF1v1.1-I05-000714, and IEEE 802.16.1-00/01r4, "Air Interface for Fixed Broadband Wireless Access Systems", September 2000.

The presently preferred PHY technique provides an optimum choice for IEEE 802.16.3 and for other applications. An important aspect of the PHY is its spectral efficiency, as this translates directly to cost measured in cost per line or cost per carried bit for FWA systems. With a frequency reuse of one and efficient support of SDMA for increased spectral efficiency, the combination of S-CDMA with FDMA is an optimum technology for the fixed wireless access market.

Benefits of the presently preferred PHY system include:

High spectral efficiency (1-6 bps/Hz system-wide), even without SDMA;

Compatibility with smart antennas (SDMA), with system-wide spectral efficiency exceeding 20 bps/Hz possible; and

A frequency reuse of one possible (increased spectral efficiency and no frequency planning).

The use of S-CDMA provides robustness to channel impairments (e.g. multipath fading): robustness to co-channel interference (allows frequency reuse of one); and security from eavesdropping.

Also provided is bandwidth flexibility and efficiency support of QoS requirements, flexibility to support any frequency allocation using a combination of narrowband S-CDMA combined with FDMA, while adaptive coding and modulation yield robustness to channel impairments and traffic asymmetries.

The use of these teachings also enables one to leverage mobile cellular technology for reduced cost and rapid technology development and test. Furthermore, cost savings are realized using the symmetric waveform and identical SS 10 and BS 11 hardware.

Having thus described the overall PHY system, a discussion will now be provided in greater detail of an aspect thereof that is particularly pertinent to the teachings of this invention.

Most cellular and fixed wireless access air-interfaces use either CDMA, FDMA or TDMA to provide logical channels to users. The instant invention employs the use of both CDMA and FDMA to provide a variable bandwidth waveform with multiple bonded transmitters and receivers that are agile in both frequency and PN code to permit a variable bandwidth and variable rate multiple access system.

There are at least two important aspects of this invention. The first is the use of both CDMA and FDMA together to provide a improved concentration efficiency by making a larger pool of bandwidth available to each user. The second aspect enables channel bonding across both code space and frequency space, thus making the system capable of operating in a variable (not necessarily contiguous) bandwidth and at a finely variable rate.

As is shown in Fig. 6, by providing multiple modulators 26A, 26B,...,26n and demodulators 34A, 34B, ..., 34n to each subscriber unit 10, and allowing multiple links to be established between each subscriber and the base station 11 with data multiplexed (multiplexer 25) across the multiple modulators 26A, 26B,...,26n at the transmitter 20 and demultiplexed (demultiplexer 33) from the multiple demodulators 34A, 34B, ..., 34n at the receiver 30, a much more flexible variable rate system is created. Modulators 26A, 26B,...,26n operate at sub-channel frequencies fA, fB,...,fn with PN codes PN_A, PN_B,..., PN_n, respectively, where n is an integer (e.g., 4, 5, 6, 7, etc.), and the demodulators 34A, 34B,..., 34n operate accordingly. In the example mentioned above, where it was desired to operate the link at 1050 kbps, a 1024 kbps channel may be bonded with a 32 kbps channel to achieve a 1056 kbps channel, thus producing very little wasted bandwidth as compared to the prior art approach. So long as the demultiplexing pattern in the receiver 30 matches the multiplexing pattern of the transmitter 20, then the link appears to effectively run at the 1056 kbps rate, and the fact that the data was actually transmitted through two separate channels is transparent to the user.

As was stated above, channel bonding, namely transmitting and receiving on multiple links in parallel to achieve additional rates, is known in CDMA systems. If, however, each modulator 26 and demodulator 34 is both frequency and code agile, then both dimensions can be utilized to provide effective rate granularity. Thus, if a subscriber unit 10 has, for example, N modulators 26 and N demodulators 34, which are each capable of communicating at rates that are power of two multiples of a basic rate on a variety of frequency subchannels, then a tremendous amount of flexibility is provided in achieving rates between those achievable by a single channel. If, for example, N equals seven, and each channel can achieve power of two multiples of 32 kbps from 32 kbps to 2.048 Mbps, then these bonded channels can achieve any integer (not just power of two integer) multiple of 32 kbps between 32 kbps and 4.096 Mbps. If one frequency subchannel is being heavily utilized by other traffic within the cell, then the BS 11 has the flexibility of reassigning some of the channels to other less-used frequency subchannels. Clearly the granularity of the variable rate effective channel is dramatically improved by bonding channels in accordance with these teachings.

A related advantage of two-dimensional channel bonding (alluded to above) is that the use of both dimensions provides a larger pool of channels to draw from, thus improving the ability to gain statistical concentration. For example, if a CDMA system has 4.096 Mbps of aggregate capacity which may be allocated to X users simultaneously at rates of 4.096/X Mbps each, then by making the modulators 26 and

demodulators 34 capable of tuning to any one of four frequency subchannels, the actual useable pool of bandwidth is four times the 4.096 Mbps bandwidth of any one channel, and 4X users can be supported simultaneously at rates of 4.096/X Mbps. This implies that, due to an improved erlang efficiency, if Y users can statistically share the X channels in one frequency subchannel, then more than 4Y users can share the 4X channels in four frequency subchannels.

Another advantage of adding frequency agility to a PN-code agile modulator 26 and demodulator 34 is that it permits the system to have flexibility in its consumed bandwidth. For example, a system that can operate only with 14 MHz wide channels cannot be used if the bandwidth allocated to the system is only 3.5 MHz. On the other hand, if a system uses CDMA/FDMA with channel bonding, then both the BS 11 and the SSs 10 have a bank of receivers that can each independently be tuned to one of a variety of frequencies, in addition to one of a variety of PN codes. If the bandwidth of any one subchannel is, for example 3.5 MHz, then by tuning some of the modulators and demodulators to each 3.5 MHz slot within a 14 MHz allocation, the bandwidth can be consumed efficiently. Thus a CDMA/FDMA system with four 3.5 MHz subchannels can operate in a 14 MHz channel, but a 14 MHz bandwidth CDMA system can not operate in a 3.5 MHz channel. Furthermore, even though a 10.5 MHz bandwidth pure CDMA system and a CDMA/FDMA system with three 3.5 MHz subchannels occupy the same bandwidth and provide approximately the same throughput when fully loaded, the CDMA/FDMA hybrid system is far more flexible. For example, if a 14 MHz frequency allocation is divided into four 3.5 MHz subchannels (labeled A, B, C and D) and subchannel C is allocated to another system, then a 10.5 MHz bandwidth pure CDMA system could not operate. In contrast, a CDMA/FDMA system could simply use subchannels A, B and D, leaving subchannel C to the other system. The ability to use non-contiguous subchannels provides operators a unique flexibility that can be very useful when attempting to add a new service to a band of frequency where some of the frequency subchannels have previously been allocated to other systems.

The use of CDMA/FDMA permits the system to occupy a variable bandwidth (either contiguous or noncontiguous). For example, a CDMA/FDMA hybrid system with four 3.5 MHz subchannels can easily operate as a 3.5 MHz system, a 7 MHz system, a 10.5 MHz system or a 14 MHz system. Again, since these do not need to be contiguous, an additional degree of flexibility is achieved over a pure CDMA system.

Another aspect to the FDMA augmentation of the CDMA system is that if there is a noisy subband within, for example, a 14 MHz band allocated to the system, then

that subband can be adaptively avoided. If the BS 11 and SS 10 are capable of detecting link quality, then they can reduce the capacity of a particular 3.5 MHz channel and place the bulk of the traffic in the less-noisy channels. This approach has the benefits of an OFDM approach without much of the complexity of OFDM.

A related benefit of this approach is that the traffic may be spread evenly across the bands if they are all equally "clean". This has the advantage that in the forward channel, where the power allocated to each channel reduces as users are added, the system can maximize the power allocated to each channel by keeping the number of active users as low as possible in each channel.

In accordance with these teachings, by bonding N modulators 26 and demodulators 34 together, and multiplexing the data to the modulators 26 and demultiplexing it at the demodulators 34, an effective channel is created that operates with a fine granularity of achievable data rates. Furthermore, the use of N modulators 26 and demodulators 34, which can each run at a unique rate on a unique code and a unique frequency subchannel, permits the link to exhibit the characteristics of occupying a flexible channel bandwidth while providing a great deal of flexibility in setting the rate of the link. The end result is an efficient utilization of the bandwidth resource.

While the invention has been particularly shown and described with respect to preferred embodiments thereof, it will be understood by those skilled in the art that changes in form and details may be made therein without departing from the scope and spirit of the invention.